2010

CS4670/PH4670, Quantum Computing [syllabus]

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Ted Huffmire and Jim Luscombe, CS4670/PH4670, Quantum Computing. Room GE-B03, Naval Postgraduate School, Monterey, CA Spring 2010.

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CS4670/PH4670, Quantum Computing, Spring 2010

Course Description:
This inter-disciplinary survey course explores the evolution and current direction of quantum computing technology. Topics include quantum circuits, quantum algorithms (including factoring and search), and quantum key distribution. You will learn to think critically about the tradeoffs of this evolving technology. Prerequisites: familiarity with basic notions of computing, quantum theory, and linear algebra, consistent with the material covered in CS3000, PH2652, MA3042 or PH3991.

Date, Time, and Location:
Mon-Tue-Wed-Thu 1200-1250 in GE-B03

Instructors:
Ted Huffmire (Computer Science)
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Grading:
Student Project, 60%
Class Participation and Student Presentations, 40%
A student presentation is required on a topic taken from the articles listed at the end the syllabus, or equivalent, with consent of instructor.

Textbook:
Yanofsky, Quantum Computing for Computer Scientists

Schedule:
Week 1: Introduction and Motivation

- Course expectations and protocols
- History of quantum computing and quantum key distribution
    - Richard Feynman, David Deutsch, Peter Shor, Isaac Chuang
- Information is physical
    - Information is registered in DNA, Neurons, Cells, Transistors, etc.
    - Depends on the laws of physics
    - Physics and Computation [Baranger00] [Fredkin92] [Margolus96]
- Fundamental Terminology
    - Landauer's Principle, Maxwell's Daemon, Schrödinger's Cat

    - Quantum bits, superposition, quantum register, Toffoli Gate, Fredkin Gate
- Why are quantum computers both more and less powerful than classical computers?

Week 2: Foundational Physics of Quantum Computing I
- History of Light
    - Thomas Young's Two-Slit Experiment
    - Birefringence: calcite crystal demo
    - Wave vs. particle experiment [Grangier86]
- Superposition and parallelism
    - Qubits vs. classical bits [Mullins01]
    - The Bloch sphere
    - The no cloning theorem
- Quantum entanglement [Rudolph08] [Salart08] [van Dam03] and teleportation
    - "Uncollapsing" [Katz08] [Merali08]
- Terminology
    - Malus' Law, Maxwell's Equations, Dirac Notation
    - Mach-Zehnder Interferometer, Pockels Cell
    - John Wheeler's Delayed Choice Experiment

Week 3: Foundational Physics of Quantum Computing II
- Entanglement and Teleportation
    - Bell States, Bell's Inequalities, Bertlmann's Socks
    - Spooky Action at a Distance
    - Teleportation vs. Quantum Key Distribution
- Einstein-Bohr Debates
    - Realism vs. Copenhagen Interpretation
    - 1935: Einstein, Podolsky, and Rosen (EPR)
    - Stern-Gerlach Experiment [Aspect82]

Week 4: Mathematical Foundations of Quantum Computing
- Quantum bits, gates, wires, and circuits [Oskin02] [Oskin03]
    - Multiple qubit gates
- Why does quantum computing need reversible computation? [Athas94] [Fredkin78] [Koller92] [Knight95] [Merkle92] [Seitz85] [Younis93]
- Why does quantum computing *need* complex numbers?
    - Applets [http://jquantum.sourceforge.net/]

Week 5: Quantum Algorithms I
- How does a quantum computer work?
    - How to represent the algorithm and data?
    - How to load the machine?
    - How to run the machine?
    - How to extract the result? Why is it hard to extract the answer?
    - What is the interface to the quantum computer?
- Deutsch's Algorithm, Deutsch-Jozsa Algorithm

Week 6: Quantum Algorithms II

- Simon’s Periodicity Algorithm [Simon94] [Simon97]
- Grover's Algorithm [Grover96]
    - How does classical search work?
- Simulation of quantum mechanical systems

Week 7: Quantum Algorithms III

- Shor's Algorithm [Shor96]
    - Why is Shor’s Algorithm a problem for public key cryptography?
    - How does classical factoring work? [Schneier95]
    - Fourier's Theorem, Classical Fourier analysis [Buskirk08]
    - What is the Quantum Fourier Transform, and how is it used to factor?
- What is the largest number factored so far on a quantum computer?
    - How long does it take?
    - Who has already built a quantum computer, and what can it do?
    - Why is it hard to design quantum algorithms? [Shor04]
- What are the quantum computational complexity classes? [Yao93] [Bernstein97]
    - What are the limitations of quantum algorithms? [Aaronson08] [Day07]

Week 8: Physical Implementations I

- Ways of creating qubits in the physical world [DiVincenzo00] [Ross08]
    - Ion traps [Metodi06] [Stick06] [Stick07] [Wineland02]
    - Quantum dots [Vandersypen07]
    - Nuclear magnetic resonance [Cory00] [Vandersypen01]
    - Superconductivity [Wendin06]
    - Semiconductor spins [Taylor05] [Morley08]
    - Holographic [Tordrup08]
    - Multilayer atom chips [Trinker08]
    - Circuit quantum electrodynamics [Blais07]
- Terminology
    - Superconductivity, Bardeen, Cooper, and Schrieffer (BCS) Theory
    - Cooper Pairs, Pauli Principle, Bose-Einstein Condensation
    - Meissner Effect, Josephson Effect, Aharonov-Bohm Effect
    - Nuclear Magnetic Resonance (NMR), Larmor Frequency

Week 9: Physical Implementations II

- Quantum Computer Architecture
- What is the price of quantum error correction? [Steane02]
    - What is quantum information theory?
- Classical control of quantum computers [Bettelli08]
    - Quantum programming languages [Omer03]
- What is distributed quantum computation?
    - Can we connect today’s puny quantum computers together to form a more powerful computer? [Curcic04]
- Terminology
    - Ion Traps, Laplace Equation, Earnshaw’s Theorem, Coulombe Force

- Linear Optics Quantum Computing
- Quantum Dots, Heterostructures, Debroglie Wavelength

Week 10: Quantum Key Distribution

- Review of classical key distribution
- The physics of QKD
  - Photons, birefringence, and polarization
- QKD algorithms and protocols [Das08] [Haitjema07] [Kuhn03] [Schneier08]
  - Information assurance issues
- Physical implementations of QKD
  - Magic Q, NSA, QKD for ships – 2003 NPS M.S. Thesis
  - DARPA Quantum Network, SPACE-Quest
- References: [Bennett84] [Bennett88] [Bennett92] [Bennett93] [Boschi98] [Bouwmeester98] [Brassard93] [Brassard98] [Deutsch96] [Ekert91] [Ekert92] [Elliot03] [Elliot05] [Gisin97] [Gisin02] [Hughes00] [Hughes02] [Kartalopoulos07] [Lemos06] [Mattle96] [Mayers97] [Mullins02] [Nguyen06] [Rabin81] [Siegfried08] [Ursin08] [Weisner83] [Zbinden97]

Week 11: Student Presentations

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